Channel Measurements of Device-to-Device Communications at 2.45 GHz

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***Abstract*—In the future, device-to-device communications will become a fundamental part of cellular communications. Interoperability between handsets will be facilitated using frequencies located in a number of bands including those found in the Industrial, Scientific and Medical (ISM) band at 2.45 GHz. In this paper, we present the results of channel measurements made between two hypothetical cellular handsets operating at 2.45 GHz in an outdoor environment. We consider a range of typical usage scenarios such as both user equipment being held at the head while imitating a voice call, placed in user's pocket for both stationary and dynamic links. A range of parameter estimates obtained using the shadowed κ–μ fading model are also presented.**

***Index Terms*—Device-to-device communications, shadowed fading, channel measurements.**

I. Introduction

Device-to-device (D2D) communications will be an intrinsic part of future cellular networks [1-4]. While participation can be overseen centrally by the network operator, the actual level of involvement may range from full control of D2D communications — where the cellular network has responsibility for control plane and data plane functions through to loosely controlled D2D communications — where operators perform access authentication only, thus allowing localized devices to setup and start D2D communications autonomously [3]. Loosely controlled D2D communications will most likely use technologies operating within the unlicensed Industrial Scientific and Medical (ISM) bands centered at 2.45 GHz and 5.8 GHz as most smart devices now come with wireless chipsets that will support at least one of these two frequencies. For this reason, this paper will focus on the characterization of D2D channels operating at the former frequency of 2.45 GHz.

The signal propagation characteristics which support D2D communications will be very different to those encountered in traditional cellular communications. In conventional cellular systems, the base stations (or eNodeB in LTE networks) are fixed and typically free of local scattering however in D2D communications, both the transmitter and receiver are in close proximity to the human body (e.g. in a pocket or held), often in motion and at relatively low elevation. Because of this D2D channels will be heavily susceptible to stochastic shadowing events caused by the direct link (dominant path) between a pair of user equipment (UE) being intersected by the user's bodies [5] and also obstacles in the local environment such as vehicles and buildings (outdoors), internal walls and furniture (indoors) and other pedestrians (both indoors and outdoors).

The shadowed κ–μ fading model [5, 6] has recently been proposed as an extension to the highly versatile κ–μ fading model [7]. In the shadowed κ–μ fading model clusters of multipath waves are assumed to have scattered waves with identical powers, alongside the presence of elective dominant signal components. The shadowed resultant dominant component, formed by the phasor addition of the individual dominant components is assumed to follow a Nakagami-m distribution. The shadowed κ–μ fading model has recently been used to characterize the received signal for D2D links operating in an urban outdoor environment at 868 MHz [5]. It was found that in scenarios where one of the user's rotated or moved randomly, the dominant signal component in the D2D link was subject to stochastic shadowing.

This paper is organized as follows. Section II introduces the experimental setup and the measurement scenarios considered in this study. Section III provides a brief overview of the shadowed κ–μ fading model and the data analysis procedure employed here. The results of the channel measurements and characterization are given in Section IV. Finally, Section V completes the paper with some concluding remarks.

II. Experimental Setup and Measurements

A. Experimental Setup

The measurement system used in this study consisted of two hypothetical user UE which both featured +2.3 dBi sleeve dipole antennas (Mobile Mark model PSKN3-24/55S) housed in a compact acrylonitrile butadiene styrene (ABS) enclosure (107 x 55 x 20 mm). This setup was representative of the form factor of a smart phone which allowed the user to hold the device as they normally would to make a voice call. It also allowed the user to carry the device in the pockets of their clothing. Each antenna was securely fixed to the inside of the enclosure using a small strip of Velcro®. The antennas were connected using low-loss coaxial cables to an ML2730 transceiver chip manufactured by RF Micro Devices (RFMD). The radio registers on the ML2730 transceiver were programmed using a PIC32MX microcontroller which acted as a baseband controller. In this study, the UE issued to person 1 was denoted UE_1 and configured to generate a continuous wave with an output power of +21 dBm at 2.45 GHz. Similarly, the UE given to person given to person 2 and herein denoted UE_2 was configured to sample the receive signal at a rate of 500 Hz.

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Fig. 1 (a) Illustration of UE positions relative to the human body and (b) plan view of the measurement environment (image courtesy of Google Maps).

$$f_R(r) = \frac{2r^{2\mu-1}}{\Gamma(\mu)}\left(\frac{\mu(1+\kappa)}{\hat{r}^2}\right)^{\mu}\left(\frac{m\hat{r}^2}{\mu(1+\kappa)\Omega + m\hat{r}^2}\right)^{m}\exp\left(-\frac{\mu(1+\kappa)r^2}{\hat{r}^2}\right){}_1F_1\left(m;\mu;\frac{\Omega(\mu(1+\kappa)r)^2}{\hat{r}^2\left(\mu(1+\kappa)\Omega + m\hat{r}^2\right)}\right) \tag{1}$$

B. *Measurements*

For all of the measurements conducted in this study, unless otherwise stated, a device-to-device link was formed between two persons, namely person 1, a male of height 1.83 m and mass 94.7 Kg, and person 2, another male of height 1.72 m and mass 75 Kg. As shown in Fig. 1(a) two primary on-body positions for the UE were considered, namely the head and pocket. For all head measurements the UE was held at a 45° angle to the vertical against the respective person's right ear to imitate a voice call. The pocket location for person 1 was a front right trouser pocket, while for person 2 it was the front right pocket (at waist level) of a hooded top.

All of the measurements conducted in this study considered a straight-line separation distance of 6 m between the two test subjects. The experiments were conducted in an outdoor environment beside the ECIT Institute in the Titanic Quarter Belfast, United Kingdom as shown in Fig. 1(b). Three different types of link dynamic were considered, these included: 1) both persons stationary and in LOS – where both users stood stationary facing one another; 2) person 1 stationary, person 2 performing random movements within a radius of 0.5 m from their starting position and 3) both persons performing random movements within a radius of 0.5 m from their starting position. Combined with the UE positioning above this analysis gave nine different possible usage scenarios. It should be noted that each of the individual measurement trials lasted 10 seconds.

III. Data Analysis

In this paper a statistical characterization of the device-to-device channels was performed using the shadowed κ–μ model presented in [5]. The probability density function (PDF) of the fading signal in this model is given in (1), where κ is related to δ, σ and μ through the relationship $\kappa = \delta^2 / 2\mu\sigma^2$, which is simply ratio of the total power of the dominant components (δ^2) to the total power of the scattered waves ($2\mu\sigma^2$) where μ is related to the multipath clustering and the mean power is given by $\hat{r}^2$. In (1), $\Gamma(\bullet)$ is the gamma function, $m = E^2\left[\Delta^2\right] / \mathrm{var}\left[\Delta^2\right]$ is the Nakagami parameter where $\mathrm{var}\left[\Delta^2\right]$ is the variance. In this instance, $\Omega = E\left[\Delta^2\right]$ is the average power of the resultant dominant component. For convenience, the *rms* signal level, $\hat{r} = \sqrt{E\left[R^2\right]}$, is removed from the fading envelopes to enable a direct comparison of the fading characteristics for both links. All parameter estimates for the PDF of the shadowed κ–μ fading model were obtained using the `lsqnonlin` function available in the Optimization toolbox of MATLAB.

IV. Results

Table I presents the parameter estimates for all of the D2D links considered in this study, which were obtained using the model given in (1). For all of the stationary scenarios considered here, the variation in the fading signal was found to be quite low and typically within a few decibels of the mean signal level. This can be observed from Table I, were the estimated κ and m parameters for these channels were quite large, suggesting a strong dominant component with negligible variation of the dominant component. For the D2D channels in which one or both ends of the link were subject to movement, the estimated κ parameters were always greater than 1, suggesting that a dominant component existed, however in some cases, the estimated m parameters were low suggesting that the dominant signal path undergoes significant shadowed fading. Two examples of these types of D2D channels are now discussed below.

TABLE I. PARAMETER ESTIMATES FOR ALL D2D CHANNELS

Scenario	$\hat{\kappa}$	$\hat{\mu}$	$\hat{r}$	$\hat{m}$	$\hat{\Omega}$
UE_1 at Head, UE_2 at Head, both Users Stationary	346	1.21	0.98	35.6	0.97
UE_1 at Head, UE_2 in Pocket, both Users Stationary	149	1.88	0.96	3320	0.99
UE_1 in Pocket, UE_2 in Pocket, both Users Stationary	633	0.76	1.21	7157	0.99
UE_1 at Head, UE_2 at Head, Person 2 Moving Randomly	1.73	1.00	1.16	0.34	0.79
UE_1 at Head, UE_2 in Pocket, Person 2 Moving Randomly	3.15	4.78	0.91	1.22	0.95
UE_1 in Pocket, UE_2 in Pocket, Person 2 Moving Randomly	4.88	1.49	1.49	1304	0.71
UE_1 at Head, UE_2 at Head, both Users Moving Randomly	4.22	1.27	1.27	0.16	1.26
UE_1 at Head, UE_2 in Pocket, both Users Moving Randomly	2.46	1.07	1.07	2125	0.79
UE_1 in Pocket, UE_2 in Pocket, both Users Moving Randomly	1.01	1.19	1.19	0.12	0.35

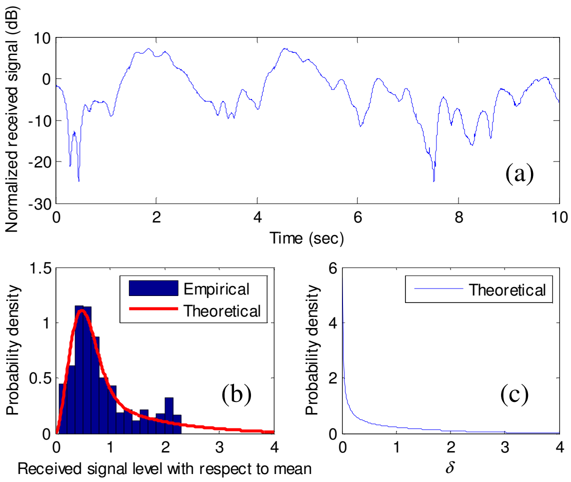

Fig. 2 (a) Normalized received signal envelope (b) empirical and theoretical PDFs and (c) PDF of the resultant dominant component for the UE_1 head to UE_2 head channel while both persons performed random movements. All parameter estimates for the PDF of the shadowed κ–μ fading model are given in Table I.

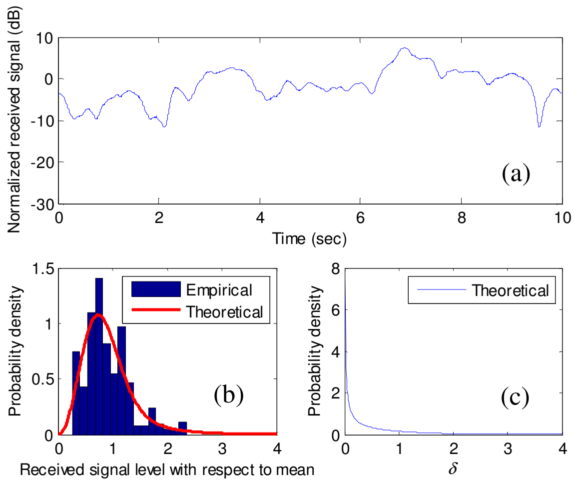

Fig. 3 (a) Normalized received signal envelope (b) empirical and theoretical PDFs and (c) PDF of the resultant dominant component for the UE_1 pocket to UE_2 pocket channel while both persons performed random movements. All parameter estimates for the PDF of the shadowed κ–μ fading model are given in Table I.

Figs. 2 and 3 show the received signal power time series for the D2D channels while both persons had the UEs positioned at their heads and then both UEs in their pockets while they both performed random movements. As we can see from Fig. 2(a), when both ends of the D2D link were held at the user's head and the persons were moving, there was a significant variation in the received signal caused by shadowing (occasionally greater than 20 dB). This was confirmed by the parameter estimates for the model given in (1). Here the estimated m parameter was 0.16 which suggests severe shadowing of the dominant component (κ = 4.22). As also shown in Fig. 2(b), is the PDF of the shadowed κ–μ fading model given in (1) which provides a very good fit to the empirical data. To illustrate the significant shadowing experienced in this scenario, Fig. 2(c) shows the estimated PDF of the resultant dominant component.

For the D2D link when the UEs were now positioned in the pocket and both persons were moving randomly, there was considerably less variation observed in the received signal [Fig. 3(a)]. Nonetheless, this link was still subject severe shadowing as shown in Table I, where the estimated m parameter was found to be 0.12. For this link, the PDF of the shadowed κ–μ model provided a reasonable fit to the measured fading channel [Fig. 3(b)]. An estimate of the PDF of the shadowed resultant dominant component for this scenario is shown in Fig. 3(c).

V. CONCLUSION

Measurements of the device-to-device channel have been made at 2.45 GHz in an outdoor environment. A range of scenarios likely to be encountered in everyday life such as user equipment being held at the head while making a voice call or carried in the pocket have been considered for both stationary and dynamic situations. The shadowed κ–μ fading model has initially been used to model these channels. The parameter estimates obtained suggest that very little shadowed fading was observed in D2D links when both persons are stationary, irrespective of whether the UE was held at the head or in the pocket. When one or both ends of the link began moving, although a dominant component was observed to exist, it was found that it can be subject to significant shadowed fading.

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